DARK ENERGY SURVEY

Followup to Filters & Calibration Strategy Workshop: Calibration

Douglas L. Tucker

DES Calibration Workshop

13 June 2008

Review: Basic Observing Strategy

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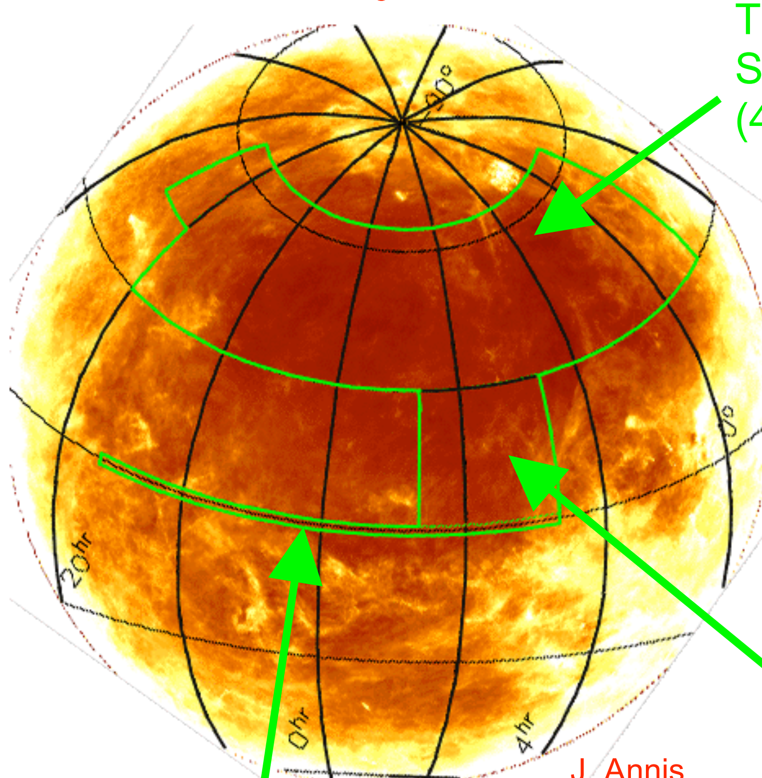
Observing Strategy

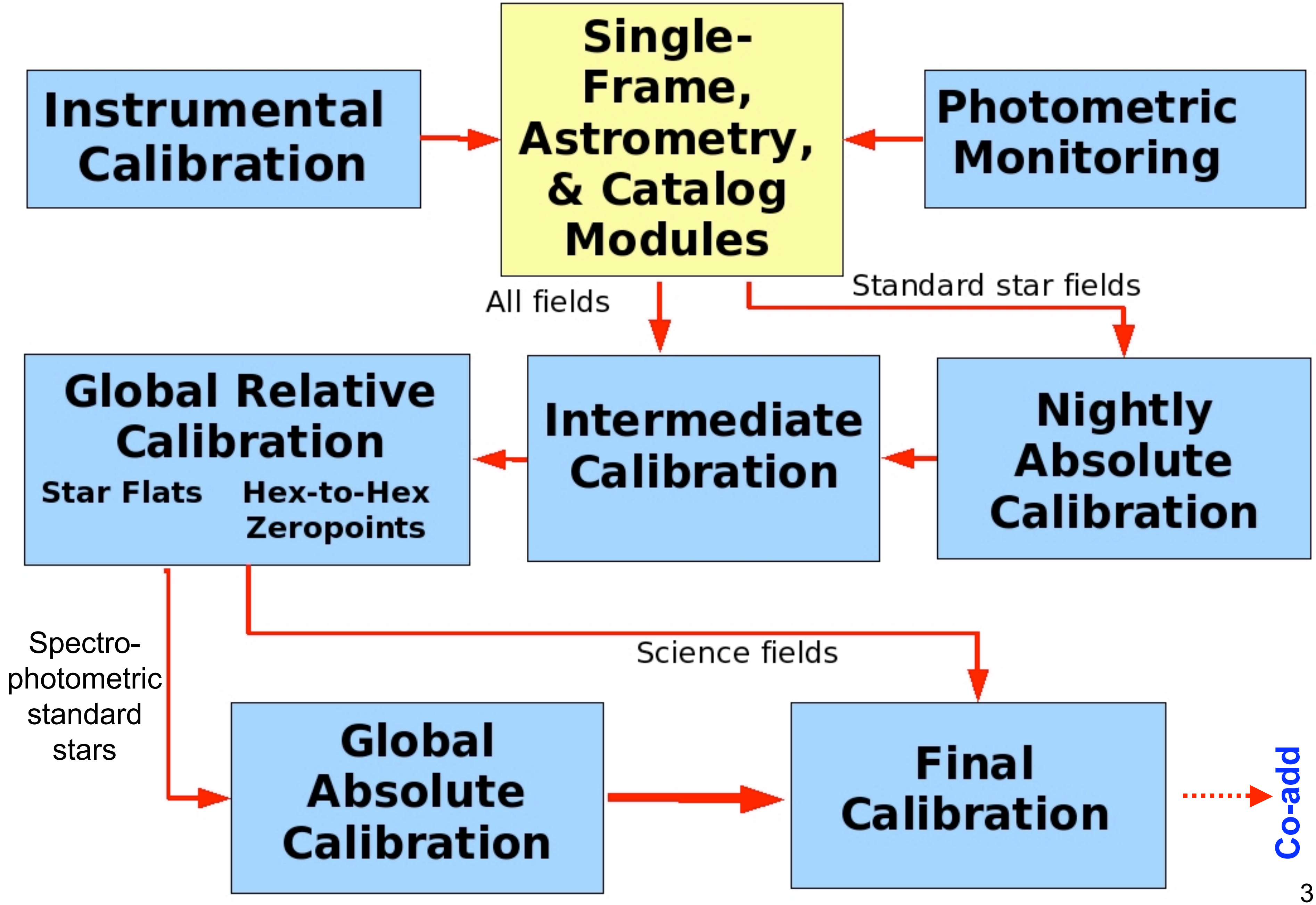
- 100 sec exposures
- 2 filters per pointing (typically)
  - *gr* in dark time
  - *iZ* in bright time
  - Y filter
- Multiple tilings/overlaps to optimize photometric calibrations
- 2 survey tilings/filter/year
- All-sky photometric accuracy
  - Requirement: 2%
  - Goal: 1%

Survey Area

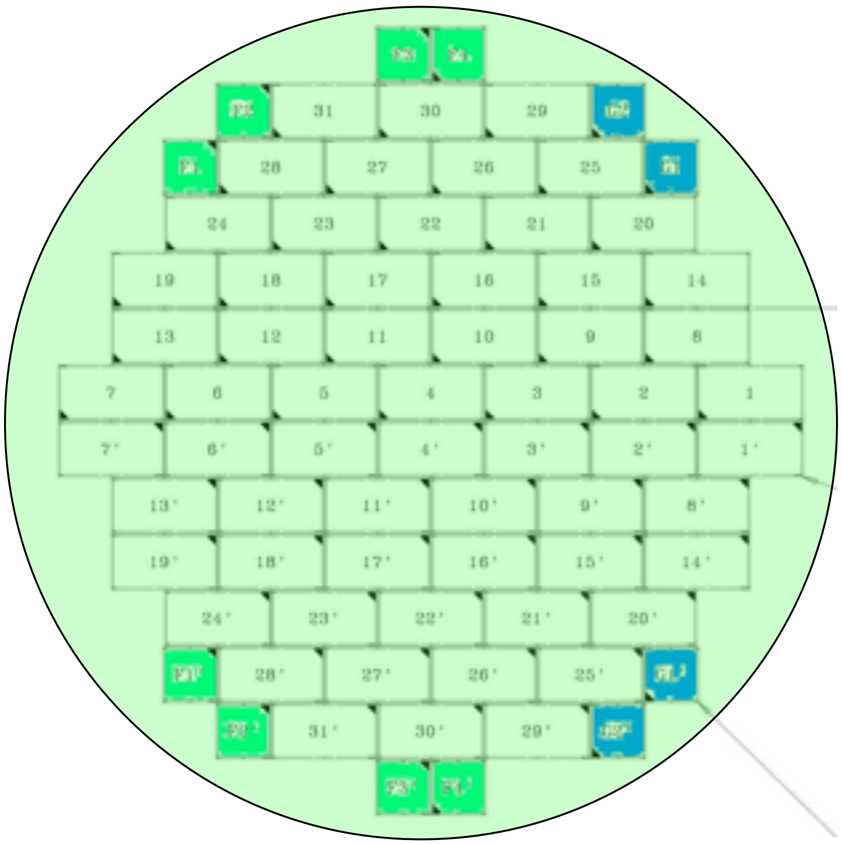


Total Area: 5000 sq deg

DES Calibrations Flow Diagram (v2)



The Problem



- There will be noticeable variations in the system response across the focal plane due to (1) CCD-to-CCD QE variations, (2) spatial non-uniformities in the coatings on C1-C5 optical elements, and (3) **spatial non-uniformities in the transmission curves of the filters**.

- Therefore, the shape of the system response response function will be a function of position on the focal plane.

- Therefore, the measured brightness of an object will depend on its position on the focal plane and on its color (shape of its spectrum).

- (Aside: Will the azimuthal orientation of the filter always be fixed, or could it move during change-outs?)

The Measurement

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Physical

laboratory

CCD QEs

Lens transmission functions

Filter transmission functions

Mirror (Al) reflectances

in situ

All in one fell swoop

Also need atmospheric transmission function.

Yield a system response function.

Needed for DES global absolute calibration (hot white dwarfs), SN program.

Astronomical

standard stars

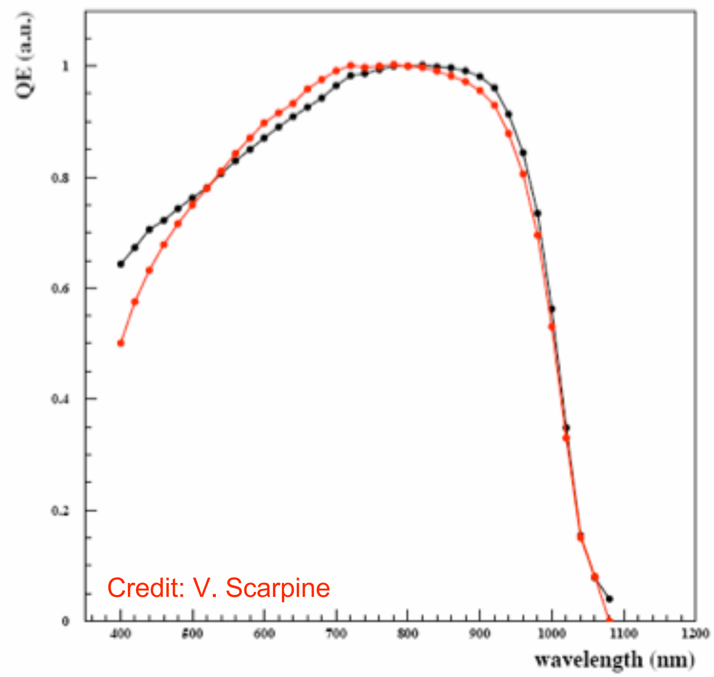
Stars of known flux covering a large range of colors (blue to red)

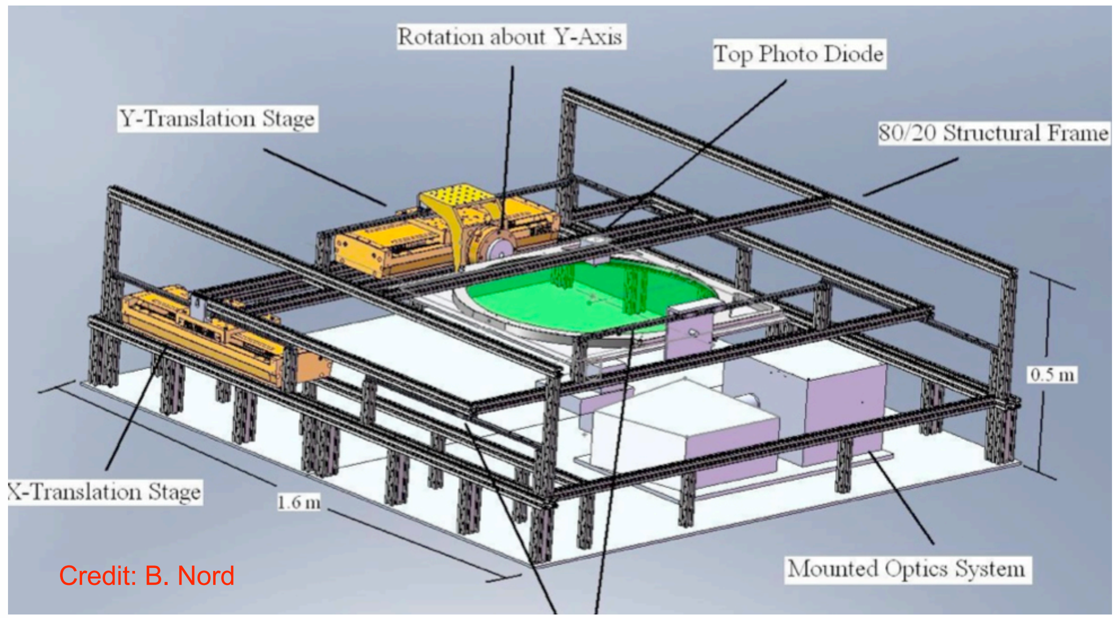
Includes effects of atmospheric transmission by default.

Traditional and robust method for tying observations to a standard photometric system.

Needed for DES nightly calibrations and global relative calibrations.

The Measurement: Physical/Laboratory





CCD QEs

- Part of DECam chip acceptance testing (accurate to ~3-5%)
- Vic Scarpine

Filter Transmissions

- University of Michigan system
- In development (Brian Nord)
- Concern expressed that we don't want to be moving $200K filters around

The Measurement: In situ (I)

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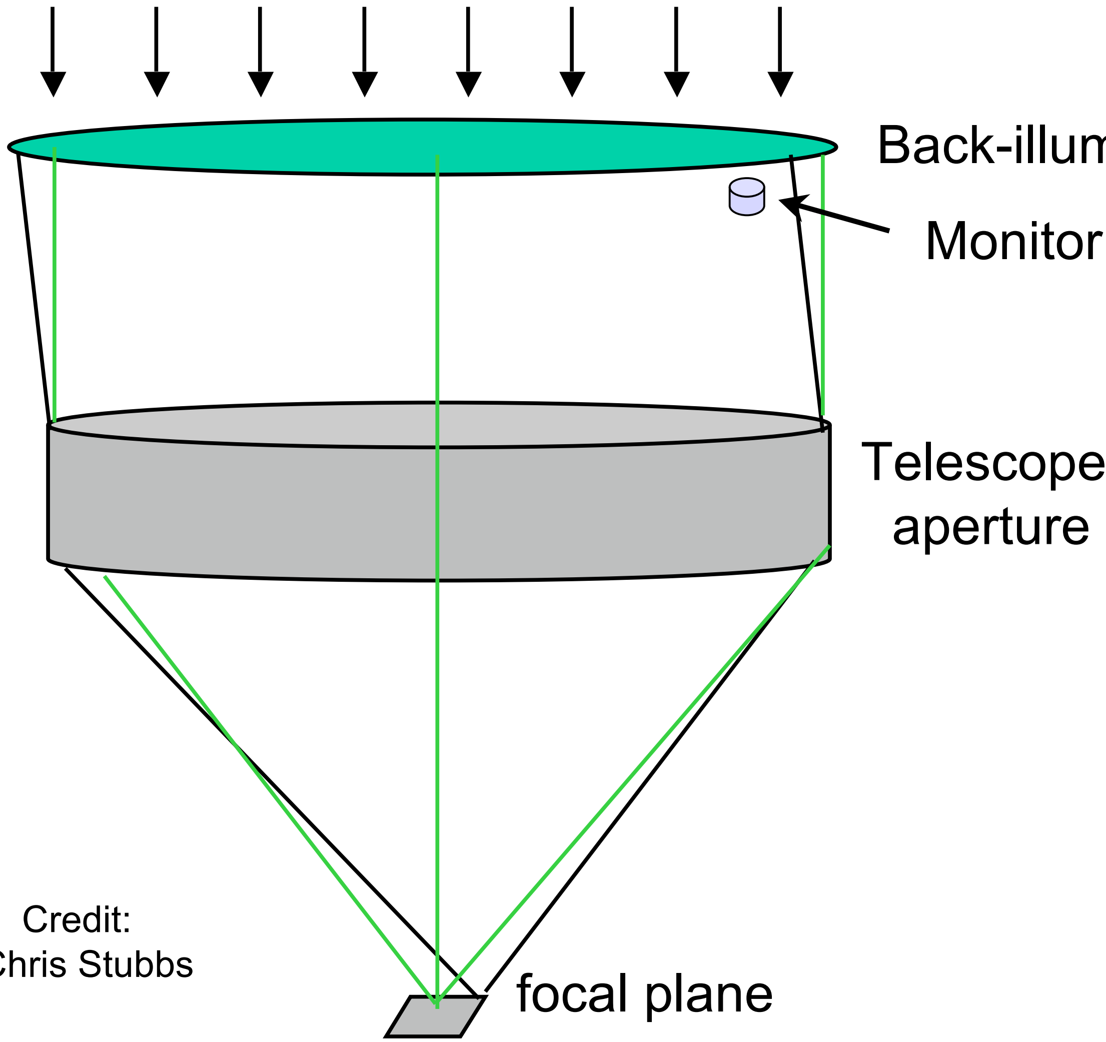
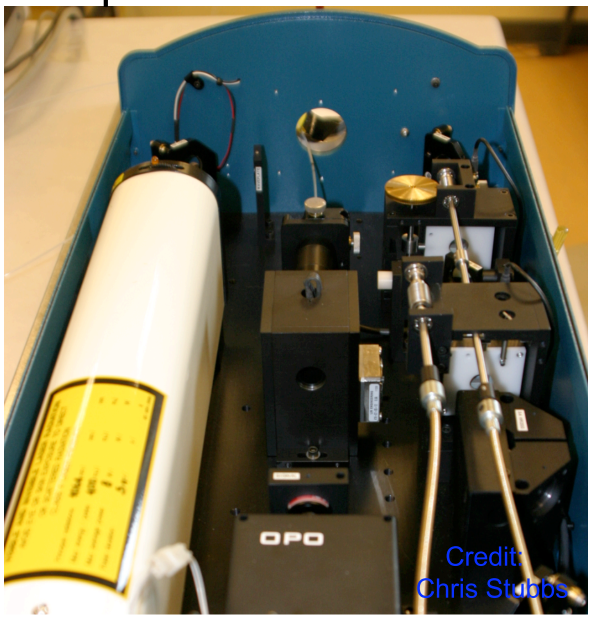
Stubbs System Response Calibration Engine

(Stubbs & Tonry 2006)

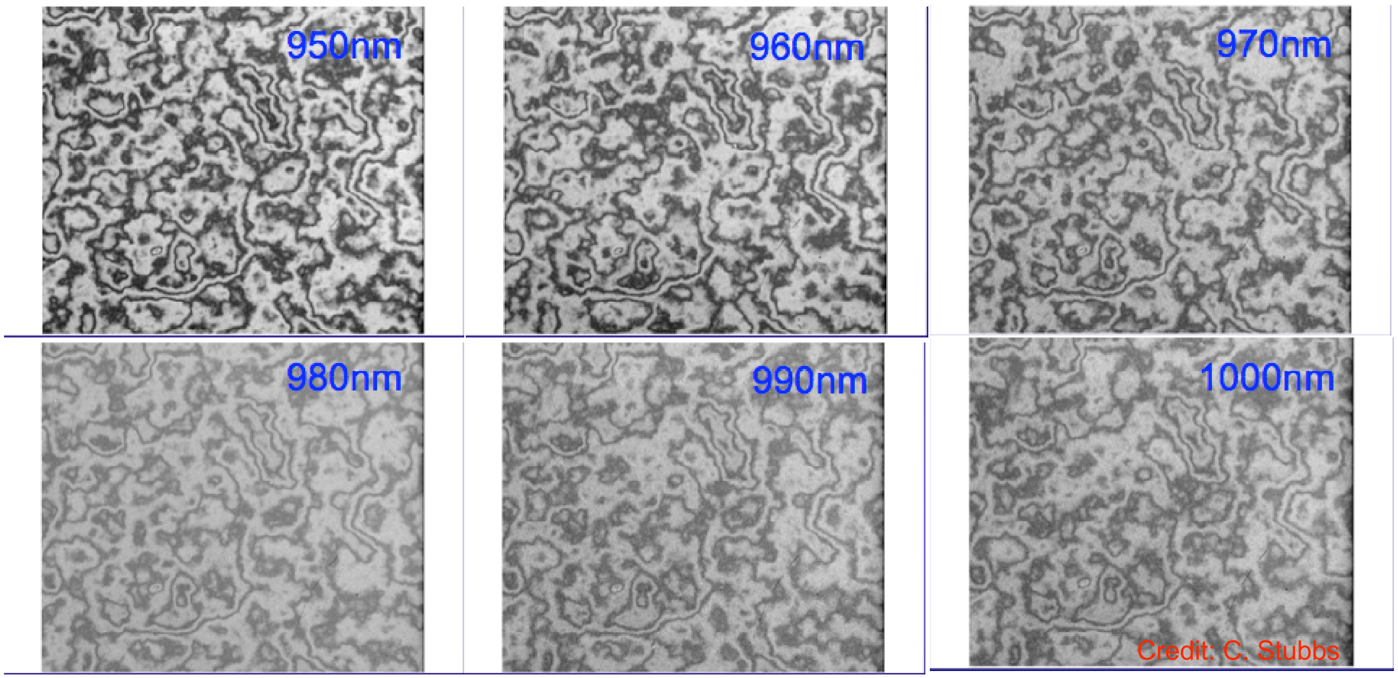


Credit:
Chris Stubbs

Opotek Tunable Laser



The Measurement: In situ (II)



Data from Blanco+Mosaic2

- A tunable laser system permits one to monochromator the full optical path from the telescope’s entrance pupil to the CCD detectors over the whole focal plane in one fell swoop.
  - filter transmission, CCD QE, and optical throughput for the Blanco+DECam
  - Fewer errors than measuring each contribution separately
  - Could possibly use LEDs instead of a laser (see, e.g., Marshall & DePoy 2005)

The Measurement: Standard Stars (I)

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- We want to fit the observed magnitudes of a set of standard stars to their "true" magnitudes via a simple model (photometric equation); e.g.:

$$m_{inst} - m_{std} = a_n + kX$$

  - m_{inst} is the instrumental magnitude, $m_{inst} = -2.5\log(counts/sec)$ (input)
  - m_{std} is the standard ("true") magnitude of the standard star (input)
  - a_n is the photometric zeropoint for CCD n (n = 1-62) (output)
  - k is the first-order extinction (output)
  - X is the airmass (input) ($X \approx \sec Z$, so X=1 overhead and X=2 at Z=60°)

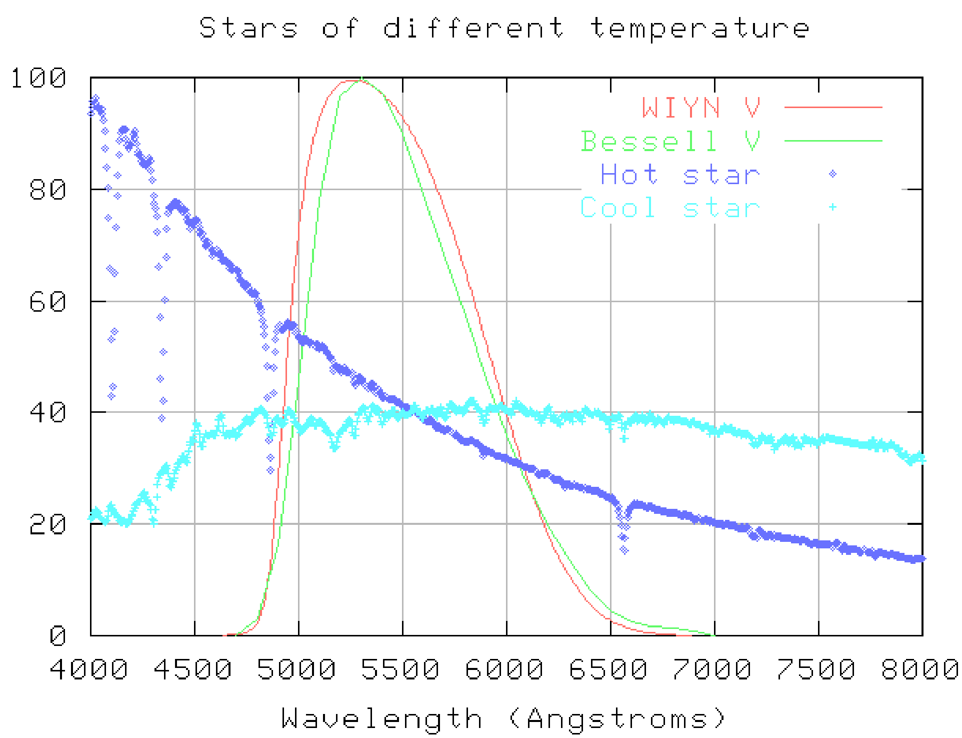
- This assumes:
  - There are no color terms needed to place the magnitudes on the standard star photometric system (i.e., the standard stars are on the "natural" system of the telescope+detector+filter)
  - The shape of the system response curve of the telescope+detector+filter does not vary substantially over the focal plane of the camera
    - Define the "natural" system using the average system response over the focal plane?
    - Define the "natural" system using a single CCD near the center of the focal plane?
    - In either case, there will be CCD-to-CCD color terms

The Measurement: Standard Stars (II)

- A refinement: add an instrumental color term for each CCD to account for small differences between the standard star system and the natural system of that CCD:

$$m_{inst} - m_{std} = a_n + b_n \times (stdColor - stdColor_0) + kX$$

  - b_n is the instrumental color term coefficient for CCD n (n = 1-62) (output)
  - *stdColor* is a color index, e.g., *(g-r)* (input)
  - $stdColor_0$ is a constant (a fixed reference value for that passband) (input)

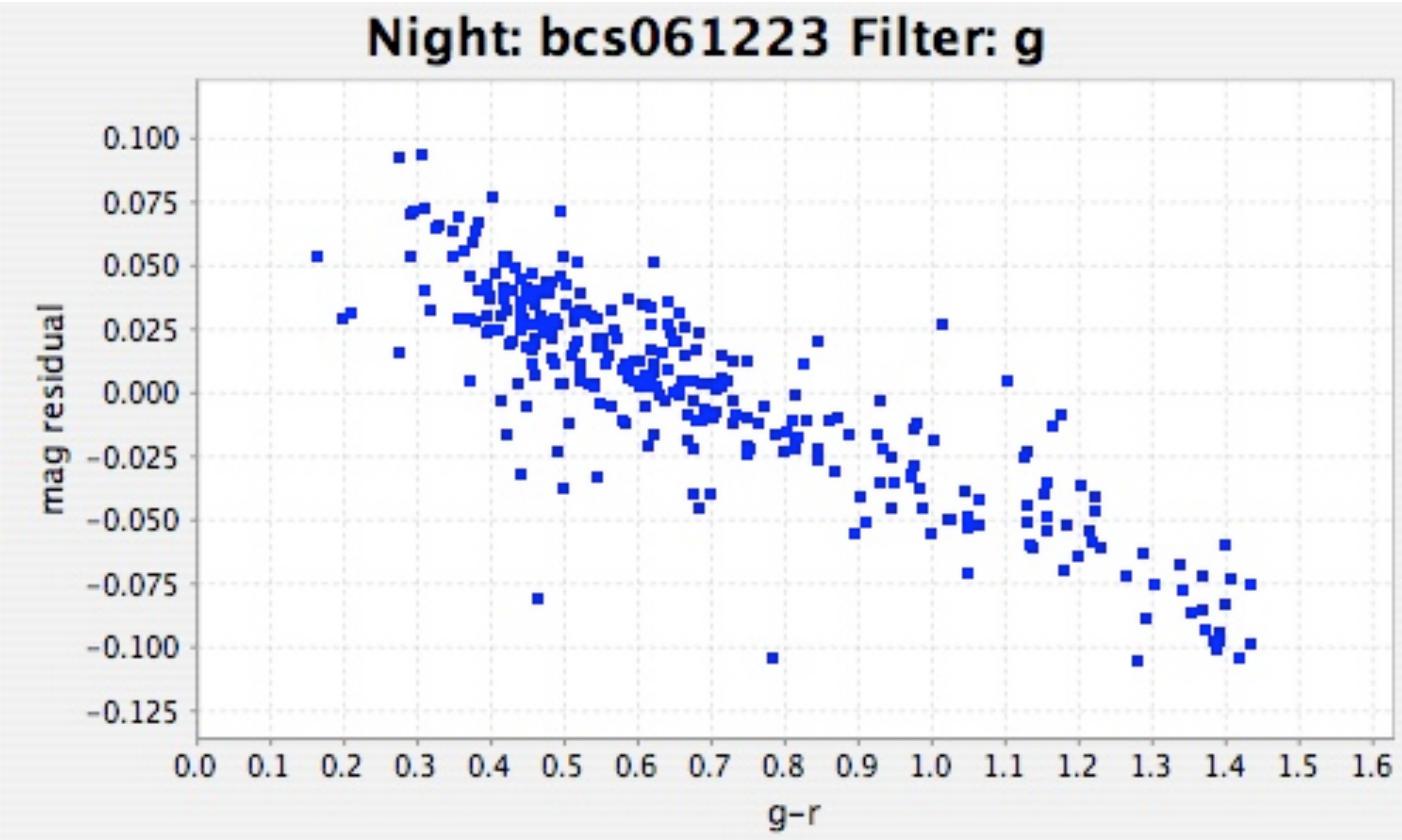


Need a set of standard stars that covers a wide range of colors

Credit: Michael W. Richmond

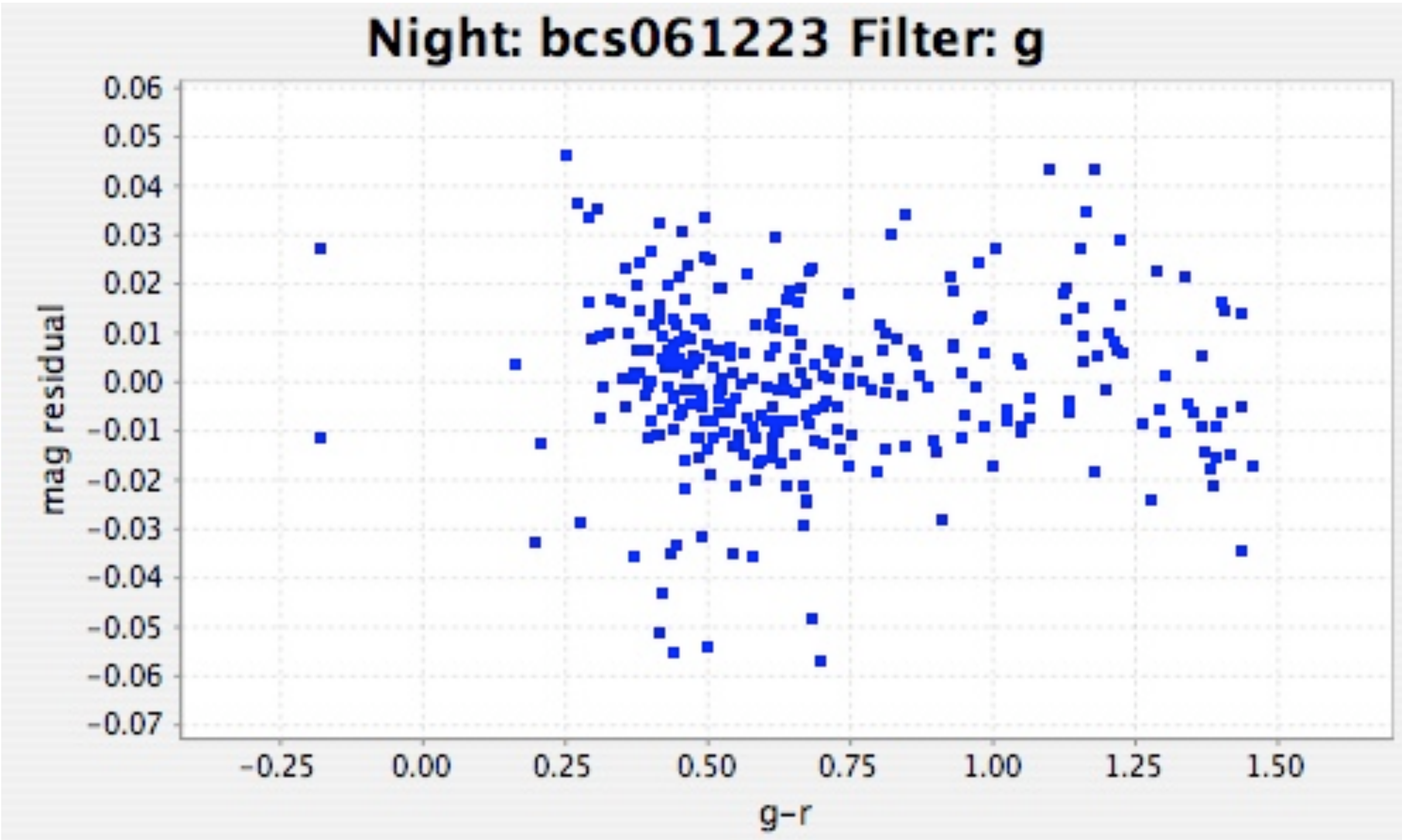
Blanco Cosmology Survey, Fixing *b*'s to 0 (rms=0.041 mag, χ^2/ν=4.24)

DARK ENERGY SURVEY



Blanco Cosmology Survey, Solving for *b*'s (rms=0.017 mag, χ^2/ν=0.74)

DARK ENERGY SURVEY

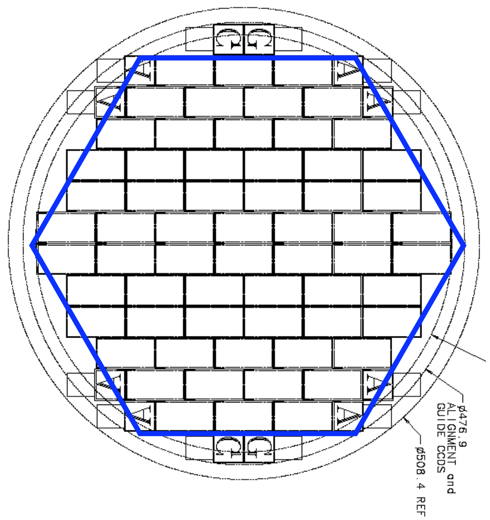


The Application: Global Relative Calibrations (pre-coadd) (I)

DARK ENERGY SURVEY

DES will not always observe under truly photometric conditions…

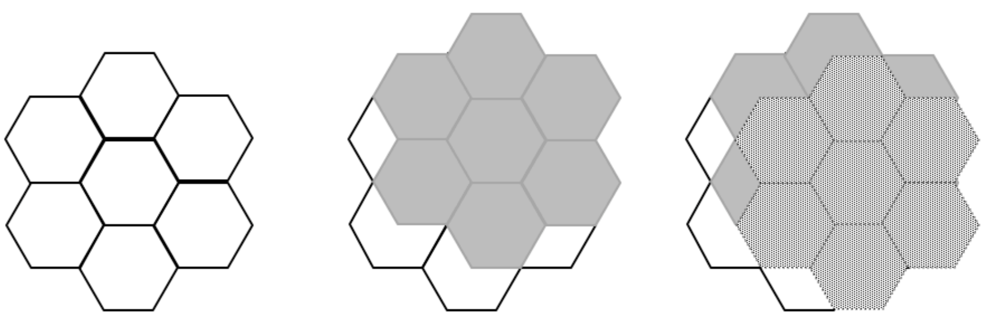
…and, even under photometric conditions, zeropoints can vary by 1-2% rms hex-to-hex.



DECam Focal Plane: “The Hex”

Jim Annis
DES Collaboration Meeting,
May 5-7, 2005

1 tiling   2 tilings   3 tilings

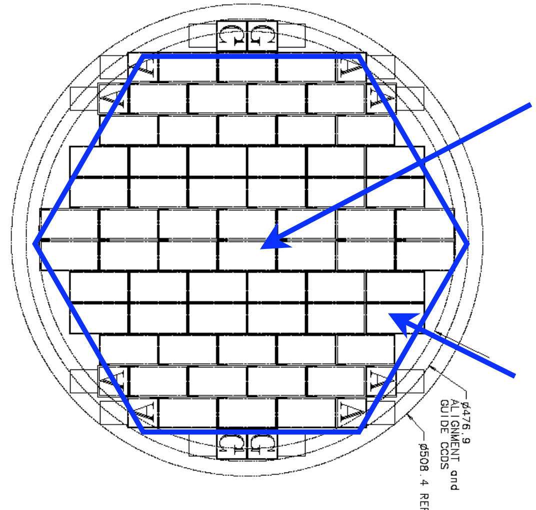


The solution: multiple tilings of the survey area, with large offsets between tilings.

We cover the sky twice per year per filter. It takes ~ 1700 hexes to tile the whole survey area.

The Application: Global Relative Calibrations (pre-coadd) (II)

What if there are non-negligible differences in the shape of the response curves for different parts of the focal plane?

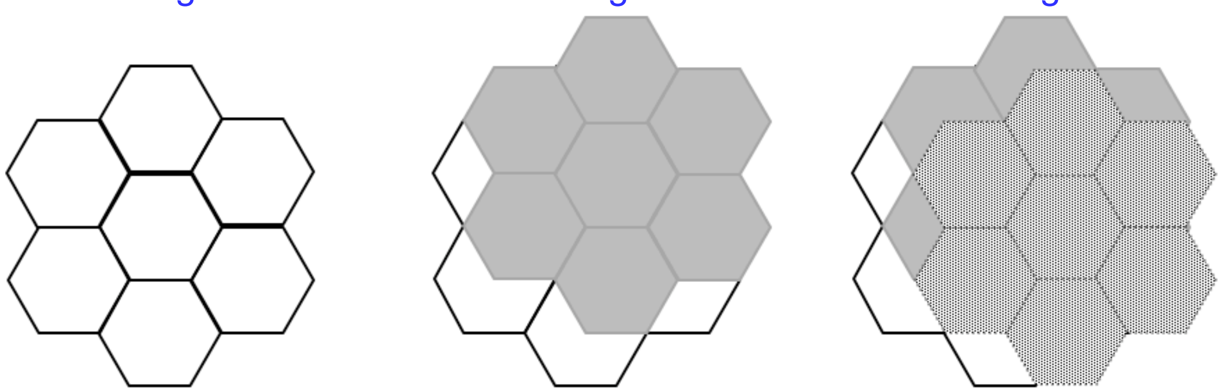


E.g., what if the system response varies from the center to the edge of the filters?

1 tiling

2 tilings

3 tilings



The Application: Global Relative Calibrations (pre-coadd) (III)

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- Variations of the system response will hopefully be quite small (1-2%) across the focal plane (and over time)
- Fit for color terms during nightly calibration and track b_n:

$$m_{inst} - m_{std} = a_n + b_n \times (stdColor - stdColor_0) + kX$$

- Initially do not apply the color terms to fields (set $b_n=0$)
- Measure and apply hex-to-hex zeropoint offsets
- Apply color terms to fields
- Iterate

(At least one iteration is necessary due to non-photometric data)

The Application: Global Relative Calibrations (pre-coadd) (IV)

DARK ENERGY SURVEY

Another Method:

- Fit for color terms during nightly calibration:

$$m_{inst} - m_{std} = a_n + b_n \times (stdColor - stdColor_0) + kX$$

- Apply the color terms to a field as soon as you have:
  - A good measure of b_n for a given CCD (b_n should not change much on daily/weekly/monthly/seasonal timescales)
  - A photometric/calibrated determination of *stdColor* for the objects in that field (this might still require an iteration)

- Let the Global Relative Calibration step only worry about zeropoint offsets and not color terms.

The Application:
Global *Absolute* Calibration (pre-coadd)

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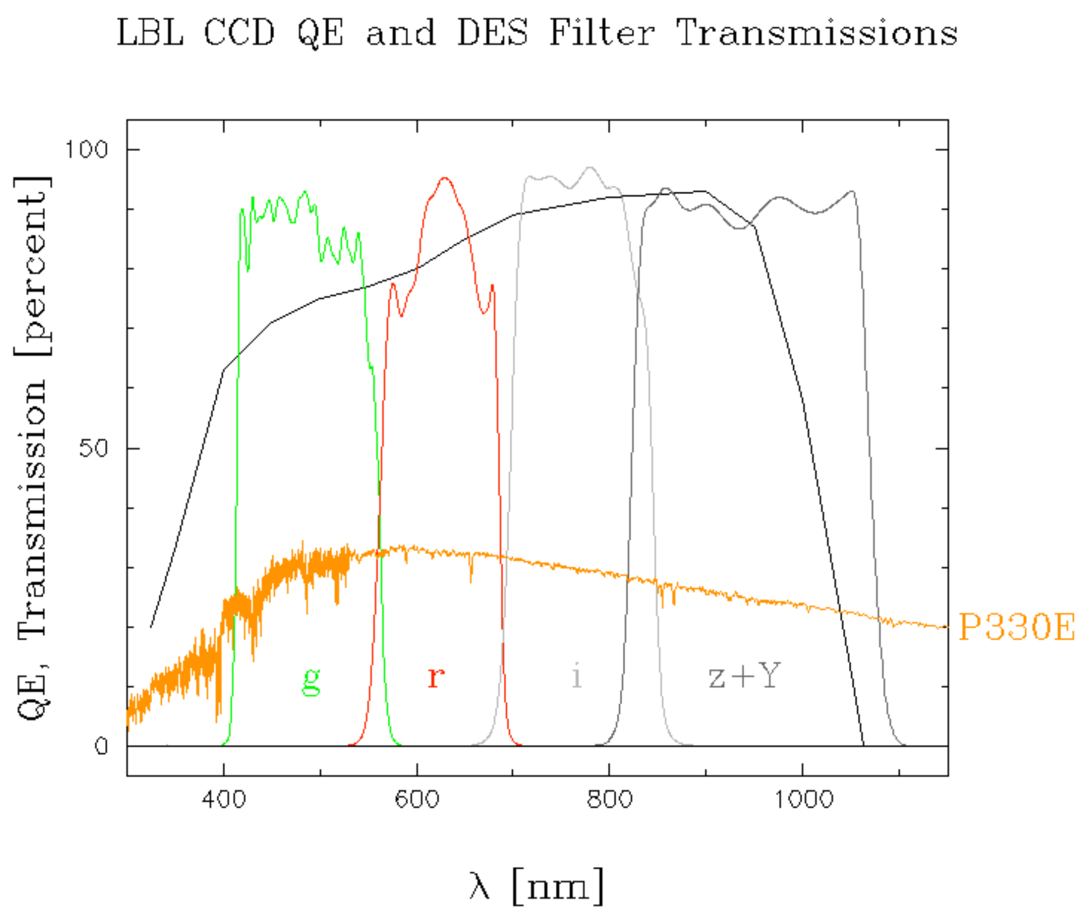
Global Absolute Calibration

- Compare the synthetic magnitudes to the measured magnitudes of one or more spectrophotometric standard stars observed by the DECam.
- The differences are the zeropoint offsets needed to tie the DES mags to an absolute flux in physical units (e.g., ergs s^{-1} cm^{-2} $Å^{-1}$).
- Absolute calibration requires accurately measured total system response for each filter passband as well as one or more well calibrated spectrophotometric standard stars.



The Application: Image Co-add

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How to do this?

- *"In traditional coadds, one averages first and asks questions later. That is, one does the coadd and then attempts a color term correction at the catalog level. It is unclear whether we can get away with this."*

  -- Jim Annis

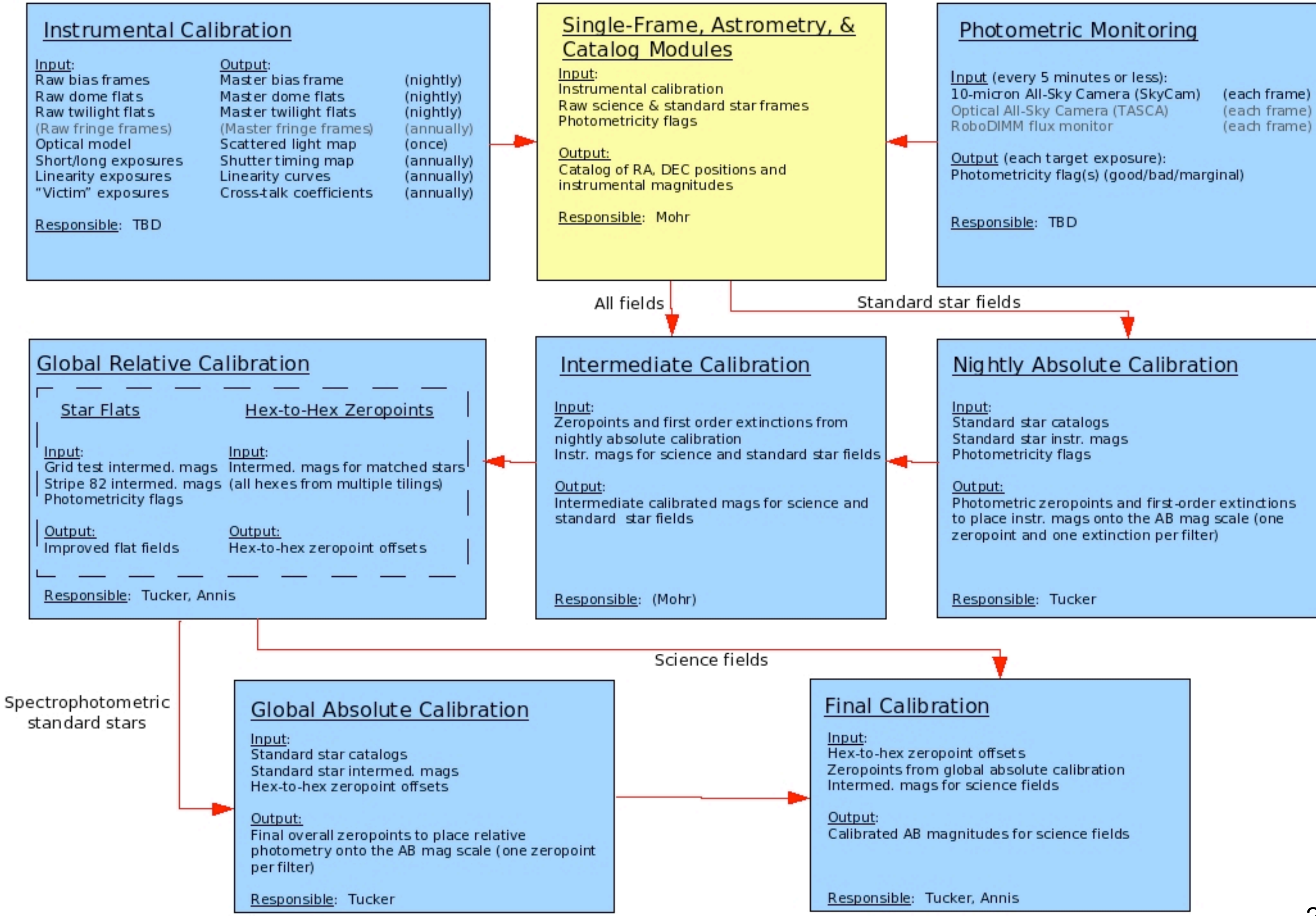
- If one ignores the spatial variation in the system response function across the focal plane, the photometry in the resulting coadd suffers.
  - Use image coadds for object detection, and (averaged?) single-epoch catalog data for the photometry?
  - Use (x,y) maps of the system response system response somehow in the image coadds? How?

Some Outstanding Questions

- What defines the DECam "natural system"? (A single CCD, the mean of a set of CCDs, …?)
- What design should be used for the system response measuring engine (e.g., tunable laser or LEDs)?
- Where is the optimal step to apply color ("*b*") terms?
- What is the best method for the image coadd?
- Are there other ways we can improve upon the methodology of photometric calibration (perhaps a more aggressive use of the system response maps rather than traditional color ("*b*") terms)?

Extra Slides

DES Photometric Calibrations Flow Diagram (v2.2)



Blanco Cosmology Survey, Fixing *b*'s to 0 (rms=0.041 mag, χ^2/ν=4.24)

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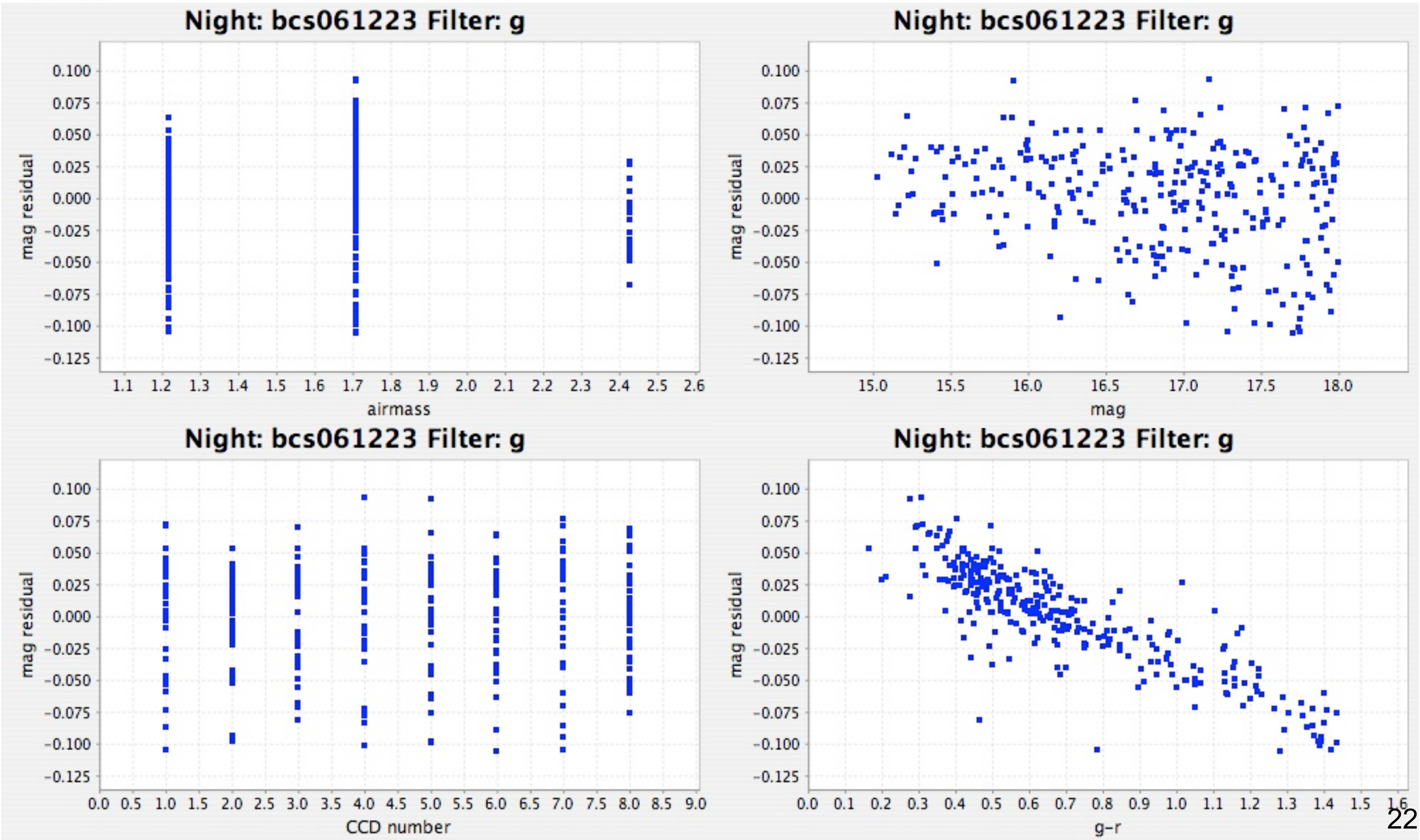
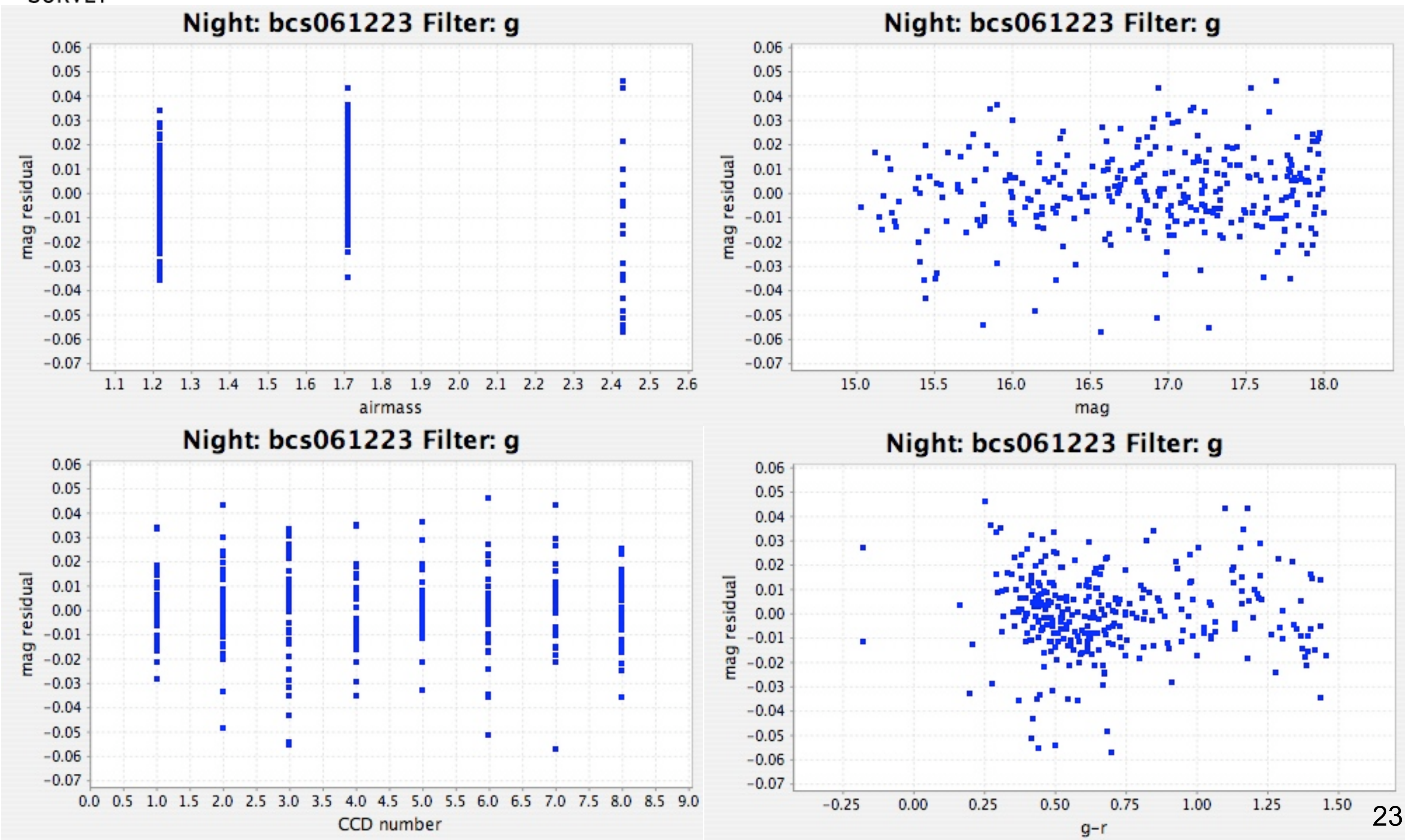
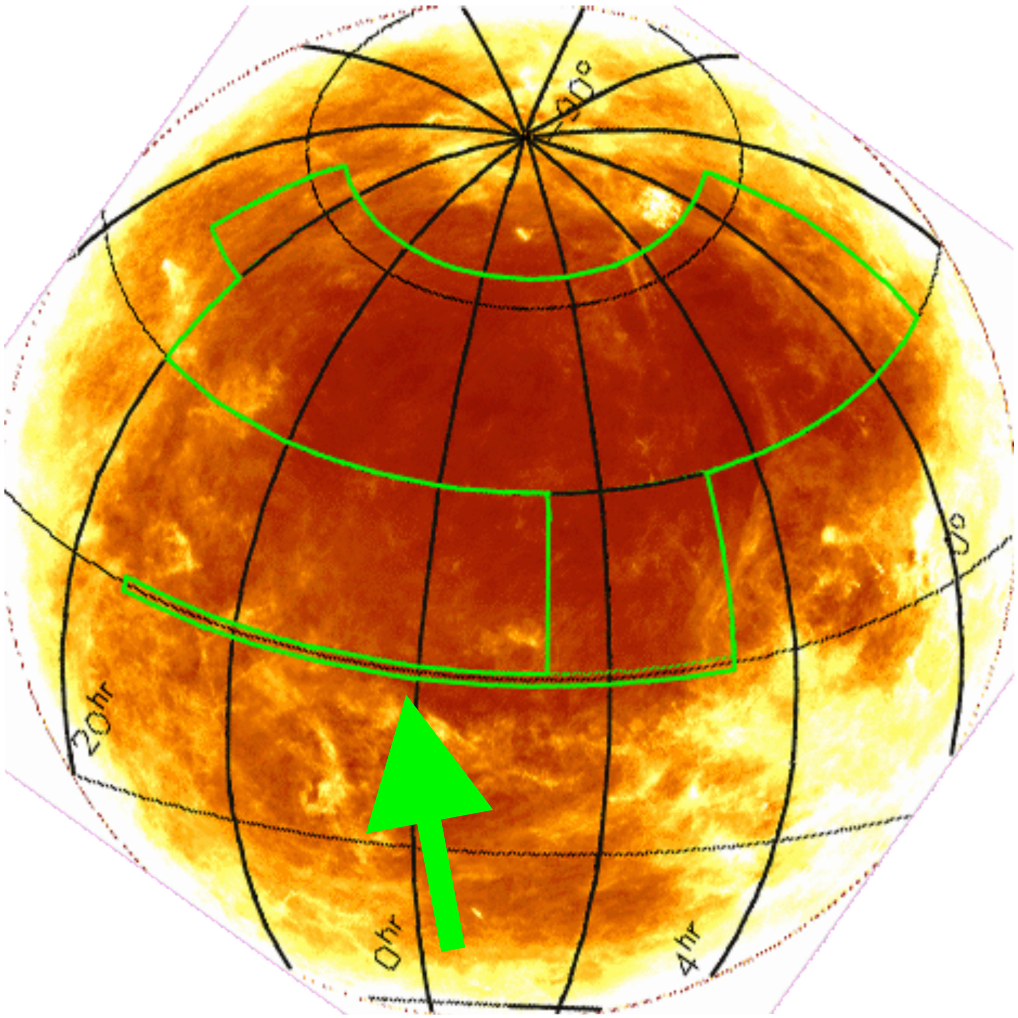


Blanco Cosmology Survey, Solving for *b*'s (rms=0.017 mag, χ^2/ν=0.74)



Nightly Absolute Calibration: SDSS Stripe 82 *ugriz* Standards



Already part of the DES survey strategy.

Readily observable at a range of airmasses throughout most nights during the DES program.

2.5° wide (compares favorably with DECam's FOV (≈2.2°).

Value-added catalogue of tertiary standards is being made

- Area of Stripe 82 has been observed by SDSS > 10x under photometric conditions
- ~ 1 million tertiary SDSS *ugriz* standards (r = 14.5 - 21)!
- ~ 4000 per sq deg (on average)
- See Ivezić et al. (2007)

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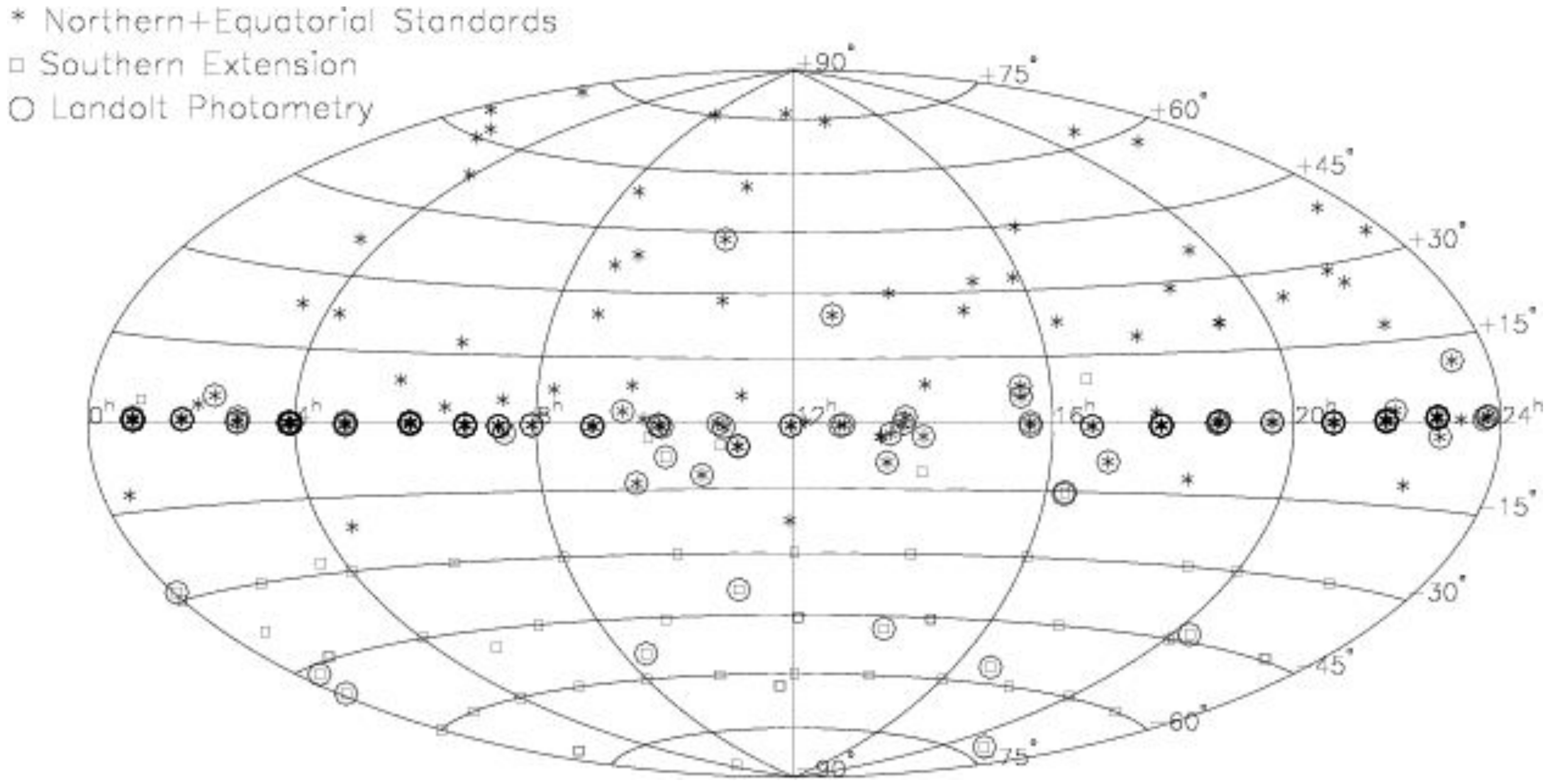
Nightly Absolute Calibration: Southern *u’g’r’i’z’* Standards



- Smith, Allam, Tucker, Stute, Rodgers, Stoughton
- 13.5' x 13.5' fields, typically tens of stds. per field
- *r* = 9 - 18, ~60 fields, ~16,000 standards

- stars as bright as r≈13 can likely be observed by DECam with 5+ second exposures under conditions of poor seeing or with de-focusing (FWHM=1.5”).

- http://www-star.fnal.gov/Southern_ugriz/

(Others: SkyMapper standards? VST OmegaCam standards? Stars from PanSTARRS-1 3π survey?)

Global Absolute Calibration: Spectrophotomeric Standards

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- ~100 Hot White Dwarfs (DA) in SDSS Stripe 82 (r=16-21)
  - Need to know temperature and log g for “true” SED (models)
  - Need high-resolution spectroscopy (ground-based) + modelling?
  - These set an absolute color scale

- LDS 749B (DES Fundamental Calibrator?)
  - In SDSS Stripe 82 (RA=21:32:16.24, DEC=+00:15:14.7; r=14.8)
  - In HST CalSpec database (STIS observations + model)
  - Sets the absolute flux scale relative to Vega (i.e., Vega taken as “truth”)

- Others
  - E.g, G158-100, GD50, GD 71, G162-66
  - All are HST WD spectrophotometric standards
  - All are visible from CTIO
  - All are V> 13.0 (won’t saturate DECam at an exposure time of 5 sec (FWHM ~ 1.5”)

Global Calibration Module : Global Relative Calibrations

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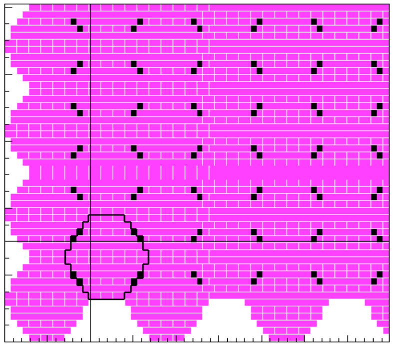
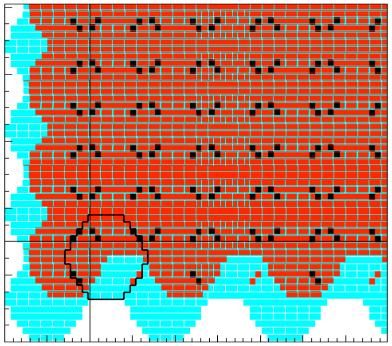
GCM Zeropoint Solver Code

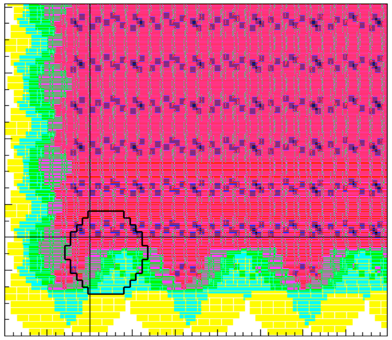
- Uses matrix inversion algorithm developed by Glazebrook et al. (1994) and used by MacDonald et al (2004).
- NxN matrix inversion, where N=# of hexes (or number of tiles or 62 x # of hexes…)
- Written in Java
- Uses cern.colt.matrix
- **Input:** An ASCII table of all unique star matches in the overlap regions
- **Output:** The ZP offsets to be applied to each field, the rms of the solution, and QA plots



1 tiling



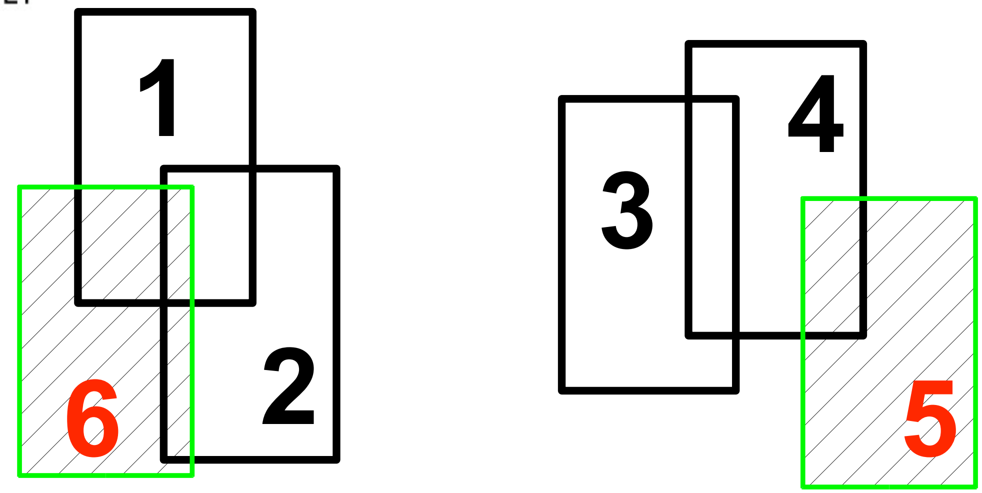
2 tilings



3 tilings

Hex-to-Hex Zeropoints
The Algorithm (I)

DARK ENERGY SURVEY



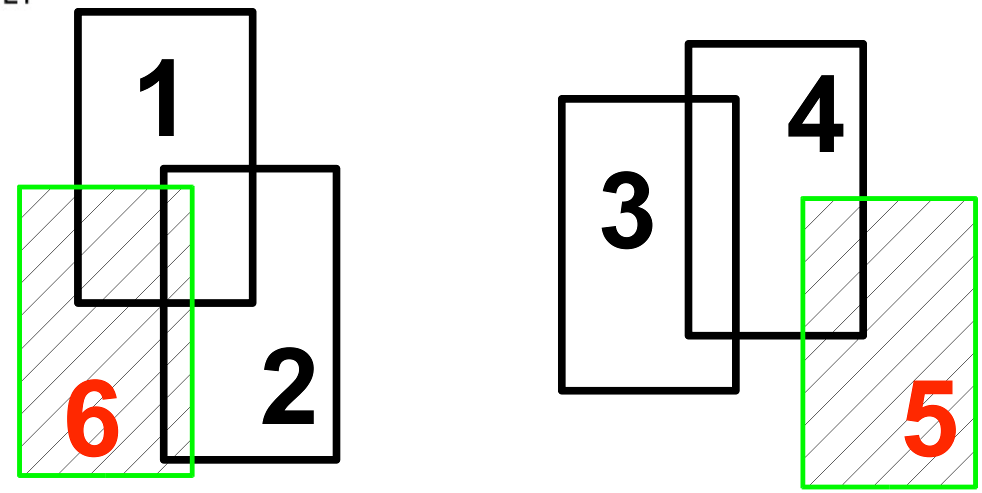
A Generic Example:
Frames 5 & 6 are calibrated.
The others are uncalibrated.

- Method used by Oxford-Dartmouth Thirty Degree Survey (MacDonald et al. 2004)
- Developed by Glazebrook et al. (1994) for an imaging K-band survey

- Consider n frames, of which (1, …, m) are calibrated and (m+1,…,n) are uncalibrated.
- Let $\Delta_{ij} = \langle mag_i - mag_j \rangle_{pairs}$ (note $\Delta_{ij} = - \Delta_{ji}$).
- Let ZP_i be the floating zero-point of frame i, but fixing $ZP_i = 0$ if i > m.
- Let $\theta_{ij} = 1$ if frames i and j overlap or if i = j; otherwise let $\theta_{ij} = 0$.
- Minimize $S = \Sigma\Sigma\, \theta_{ij}\, (\Delta_{ij} + ZP_i - ZP_j)^2$

Hex-to-Hex Zeropoints: The Algorithm (II)

DARK ENERGY SURVEY



Example:
Frames 5 & 6 are calibrated.
The others are uncalibrated.
(From Glazebrook et al. 1994)

$$\begin{vmatrix} -2 & 1 & 0 & 0 & 0 & 1 \\ 1 & -2 & 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{vmatrix} \times \begin{vmatrix} ZP1 \\ ZP2 \\ ZP3 \\ ZP4 \\ ZP5 \\ ZP6 \end{vmatrix} = \begin{vmatrix} \Delta_{12} + \Delta_{16} \\ \Delta_{21} + \Delta_{26} \\ \Delta_{34} \\ \Delta_{43} + \Delta_{45} \\ 0 \\ 0 \end{vmatrix}$$

Nightly Absolute Calibration: Standard Star Observing Strategy

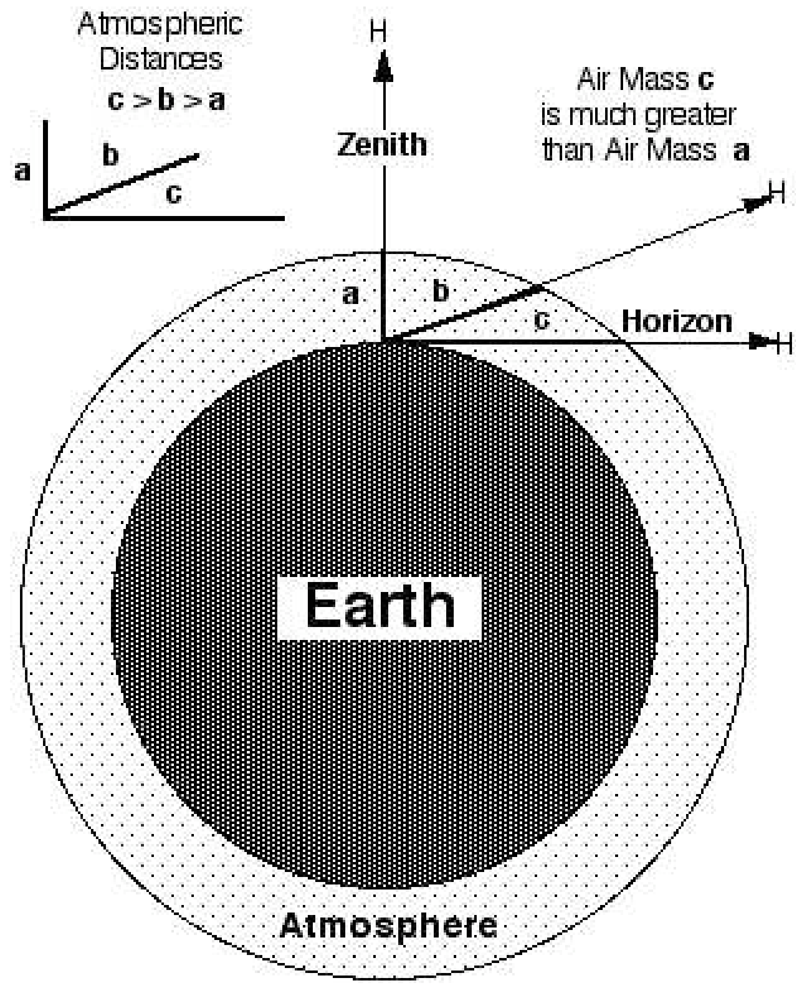
- Observe 3 standard star fields, each at a different airmass (X=1-2), between nautical (12°) and astronomical (18°) twilight (evening and morning).

- Observe up to 3 more standard fields (at various airmasses) throughout the night

- Also can observe standard star fields when sky is photometric but seeing is too poor for science imaging (seeing > 1.1 arcsec)

- Use fields with multiple standard stars (to cover focal plane and to cover a wide range of colors)

- Keep an eye on the photometricity monitors



Airmass $X \approx \sec Z$

X=1 overhead, X=2 at Z=60°